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OVERVIEW OF DISK PULVERIZATION AND ELECTROHYDRAULIC COMMINUTION

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OVERVIEW OF DISK PULVERIZATION AND ELECTROHYDRAULIC COMMINUTION

by
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ABSTRACT

Various means of comminution and their mechanisms are briefly reviewed with an emphasis on electrohydraulic comminution. These are shock wave comminution including the Snyder process, hydraulic comminution and mining, ultrasonic comminution, and elelctrohydraulic comminution; conventional mechanical comminution including various crushers, mills and disk pulverizers; and thermal comminution includiong low temperature cryogenic, high temperature thermal, electrothermal, electromagnetic, laser, electron beam, micro-wave and electroacoustic comminution.

Conventional mechanical comminution is very inefficient in terms of energy used to produce new surface area. Among many mechanical comminution devices, it is recognized that a disk pulverizer deserves a further concerted R&D effort. Although it has some shortcomings such as high rate of disk wear and low throughput, its plane contact grinding mechanism stands out from mechanisms of other comminution devices that use line or point contact. The contact period of the working surface is 100 % of the operating time. It utilizes low shear stress rather than high compressive stress to break solid particles. As in a flywheel, large rotating disks can save energy as angular momentum. By-passing of solids is not possible. Consequently, the utilization of comminution energy will be high in disk pulverization.

Electrohydraulic comminution occurs when a shock wave is generated using an electric spark in water containing solid particles. Although a large scale industrial application of the process is yet to be realized, it has long term potential to achieve high efficiency of comminution energy. The process, however, even at the present time, may find limited use for some specific applications, e.g. non-contact comminution of radioactive materials, contamination-free comminution of optical glass, or non-explosive and non-mechanical breakage of rocks. All other non-contact means of comminution are at early stages of development and are far from being practical enough for the application in mineral processing industry at the present time.

Keywords: Comminution Energy, Disk Pulverizer, Mechanical Comminution, Thermal Comminution, Shock Comminution, Electrohydraulic Comminution, Ultrasonic Comminution, Cryogenic Comminution, Laser Comminution, Electron Beam Comminution, Micro-wave Comminution, Electroacoustic Comminution, Snyder Process, Hydraulic Mining, Electrohydraulic Drilling

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CONTENTS

	page
ABSTRACT	i
RÉSUMÉ	ii
I. INTRODUCTION	1
II. FORCES FOR COMMINUTION	1
III. MEANS OF COMMINUTION	2
CHEMICAL COMMINUTION	2
SHOCK WAVE COMMINUTION	2
Snyder Process	2
Hydraulic Comminution and Mining	3
Ultrasonic Comminution	3
Electrohydraulic Comminution	3
MECHNICAL COMMINUTION	3
Low Energy Efficiency of Mechanical Comminution	3
Disk Pulverizer	4
THERMAL COMMINUTION	5
Cryogenic Comminution	5
High Temperature Thermal Comminution	5
Electrothermal Comminution	6
Electromagnetic Comminution	7
Laser Comminution	7
Electron Beam Comminution	7
Micro-wave Comminution	8
Electroacoustic Comminuiton	8
IV. ELECTROHYDRAULIC COMMINUTION	8
PRINCIPLE	8
ENERGY EFFICIENCY OF ELECTROHYDRAULIC COMMINUTION	9
POTENTIAL BENEFITS	10
POTENTIAL PROBLEMS	11
DEVELOPMENT HISTORY	11
SELECTIVITY IN ELECTROHYDRAULIC COMMINUTION	13
PARTICLE SHAPE OF PRODUCT	13
LOW CONTAMINATION OF ELCTROHYDRAULIC COMMINUTION	14
ELECTROHYDRAULIC DRILL	14
V. CONCLUDING REMARKS	15
REFERENCES	17

OVERVIEW OF DISK PULVERIZATION AND ELECTROHYDRAULIC COMMINUTION

I. INTRODUCTION

Comminution has been vital to sustaining the life of Homo Sapiens since prehistory, when man learned to make tools for hunting, excavation and arms using broken pieces of rock. Without the natural comminution process called erosion, there would have been no surface soils and consequently, no life of the present form on our planet. Human beings still use the same primitive means of comminution, their molars, to process food. However, some complicated processes of comminution have been developed with the advent of modern civilization, and they are required for virtually all industrial activities of present days.

By the nature of mineral processing, the comminution of mineral-containing rocks starts the process of winning the valuables from natural resources. The comminuiton of rocks includes various mining activities as well as crushing and grinding in mineral processing. Comminution in mineral processing is done to liberate different minerals, to produce proper particle size and shape, and for the easy handling of materials. Since the proper liberation of minerals is the key to any successful separation of them, comminution is recognized as a key process that affects the efficiency of subsequent separation processes.

Conventional mechanical comminution is notoriously inefficient with respect to its energy usage in generation of new surface area due to many reasons, as will be discussed in detail in a latter section. In this paper the general mechanism of comminution and the various means of comminution are reviewed briefly to identify the area of potential improvement. Current status of disk pulverization and electrohydraulic comminution, the two processes that appear to be most promising, are reviewed in more detail.

II. FORCES FOR COMMINUITON

Comminution is the process by which particle size is reduced and particle shape is altered, while the identity of the original materials is kept unaltered. Comminution is effected by the breakage of atomic and/or molecular bonds in solids and is the result of overwhelming tensile stress. Compression and shear stresses also can increase the local tensile stress to cause the breakage of bonds. In most systems of comminution, however, all three stresses are involved in breakage.

III. MEANS OF COMMINUTION

The means of comminution can be either physical or chemical. In rare cases of chemical comminution chemical reagents are used to attack particular bonds in solids, resulting in the reduction of particle size. On the other hand, physical comminution utilizes mechanical, thermal, electrical and various shock wave forces.

CHEMICAL COMMINUTION

Chemical comminution of coal by solvents was observed first by Banham and Fakhoury (1931). Liquid sulphur dioxide and carbon dioxide have been studied, but ammonia resulted in the best chemical comminution of coals for the liberation of mineral matter from coals (Aldrich, Keller and Sawyer, 1974 & 1975, Keller and Smith, 1976, Datta, Howard and Hanchet, 1976, Howard and Datta, 1977, Data and Howard, 1978, Anonymous, 1980, Burow and Glavincevski, 1980).

SHOCK WAVE COMMINUTION

Chemical explosion has been used extensively in mining to break up rocks and even nuclear explosions (Coffer, Grier and Aronson, 1968 and Evans and Weir-Jones, 1973) have been studied as a possible means of ground breakage for certain large-scale civil engineering works. Breakage of weak bonds can be caused by the traveling front of shock waves, as in the breakage of a window pane by supersonic boom. Rapid expansion of a high pressure fluid medium can produce an acoustic shock wave strong enough to cause particles to break. Indeed this is one of the main mechanisms in fluid energy comminution, as developed by Dean and Gross (1932 and 1933), Gross (1934 and 1938), Dean, Gross and Wood (1935) and Gross and Wood (1935), all at the U.S. Bureau of Mines.

Rinehart and Davids (1960) and Kolsky (1963) indicated that partial reflection of the initial shock wave induces the local tensile stress at the opposite side of the solid particle to cause "scabbing", or Hopkinson fracture. Secondary fracture may result from other phenomena such as Rayleigh surface waves (Bowden and Field, 1964) and interparticle collisions.

Snyder Process

Using the same principle of shock wave comminution, according to Cavanaugh (1972 and 1973), Cavanaugh and Rogers (1973) and Mohanty and Narasimhan (1982), the Snyder Process utilizes the sudden release of high pressure steam or air to give selective breakage along grain boundaries. The shock waves travel through a fluid medium and solid particles.

Hydraulic Comminution and Mining

Hydraulic mining utilizes a high pressure water jet (up to 1,500 MN/m^2 or 220,000 psi), as reported by Brook(1972). Grimley (1973) described successful underground hydraulic mining of coal at Kaiser Resources in British Columbia. Farmer and Attewell (1963) described the breakage mechanism of solids by high speed water droplets. According to them, the speed of the jet stream is an important factor up to certain level, but at very high speed the mass of water droplets become a dominant factor. High pressure water jet cutting has been studied extensively by Maurer (1968), Maurer and Heilhecker (1969), Brook and Summers (1969), McClain and Cristy (1970), Wyllie (1971), Savic, Allan and van Blokland (1972), Crow (1972), Forman and Secor (1973) and Harris (1973). The high pressure water jet is good for breaking loose rocks and coals, but is less useful in commiution of fine particles unless two streams of pulp are directed against each other as in the Snyder process discussed in the previous section.

Ultrasonic Comminution

A shock wave can be created in water by ultrasonic means. Martinez (1963) studied the fibrization of crysotile asbestos using ultrasonic energy. The ultrasonic treatment improved the fibrization, resulting in an enhanced filtration. Goldberger, Epstein and Parekh (1982) and Parekh, Epstein and Goldberger (1984) indicated that ultrasonic secondary breaking of molybdenite porphyric ore occurred along the grain boundary of molybdenite and pyrite within the matrix of silicate minerals.

Electrohydraulic Comminution

An underwater electric arc can generate a hydraulic shock wave (Sarapuu, 1973 and Bergstrom, 1961) to be used in metal forming or in size reduction. The subject of electrohydraulic comminution will be reviewed in more detail in a later section.

MECHANICAL COMMINUTION

Low Energy Efficiency of Mechanical Comminution

Almost all comminution in mineral processing is done using various types of mechanical equipment. They include crushing (e.g. gyratory, jaw, impact, roll and cone crusher) and grinding (e.g. rod, ball, semi-autogeneous, autogeneous, tower and vibration mill). The basic modes of comminution used by this equipment have not been changed since they were introduced to the mineral industry early in this century. The energy efficiency of these mechanical comminution equipments is notoriously low, at 1-5 % in terms of the generation of new area. According to

Parekh, Epstein and Goldberger (1984), only 0.7 % of the energy is used for the generation of new surfaces in conventional ball mill grinding. The energy losses consists of thermal loss to air (32.0 %) and to solids (48.6 %), transmission loss (14.4 %) and electric component loss (4.3 %). The same authors indicated that comminution of ores in the U.S. consumed 32×10^9 kwh (115×10^{12} kJ) of electric power, which is about 2 % of total power production in 1981. Considering the fact that energy constitutes more than half the cost of comminution, and that comminution is responsible for almost half of all costs in mineral processing (Agar, 1976), the improvement of energy efficiency in comminution is one of the key areas that require further R & D in mineral processing.

The low energy efficiency of mechanical comminution can be caused by many reasons. The massively heavy comminution mechanim must be operated at all times during comminution. The operation of the comminution mechnism itself requires high energy, even without any solid charge. This is particularly true in grinding. In many cases, the working surface is limited to a very small portion of the total contact surface at any given time. For example, the majority of comminution occurs when solid particles are located at the contacting point (ball mill or vibration mill), line (rod mill or crushing roll) or plane (disk pulverizer) at the right moment. There is a cyclic relationship between active working and passive idling periods even for working grinding media. Some of the solid material may even by-pass the comminution process altogether. Consequently, the direct contact between comminution media and solids is limited to a fraction of comminution time as well as to a fraction of the working surface of the comminution media, resuting in poor utilization of comminution energy. Therfore, in order to increase energy efficiency in comminution, the contact area must be increased, and at the same time, the contact period must be increased. A plane contact mechanism will be more efficient than line contact, which in turn is more efficient than a point contact one.

Disk Pulverizer

Considering the factors mentioned in the above section, disk pulverizing is considered to be more efficient than other mechnical comminution methods. Its mode of comminution is plane contact which is in continuous contact, and the by-passing of solids is not possible. The rotating disk can function as a flywheel to store energy as angular momentum. However, industrial applications of disk pulverization have been restricted to relatively small scale operations, because the intensive energy input in the form of shear stress on a relatively small contact surface causes an exessively high rate of disk wear. The high wear of pulverizing disks can contaminate the ground

product. For some applications, use of ceramic disks in place of steel ones can eliminate contamination by iron. In the meantime, a simple mechanism for the frequent replacement of pulverizing disks has to be developed. Sometimes disk pulverizers produce flaky product. At the present time, disk pulverizers up to 1.5 m diameter are being used, mainly in the food processing industry.

THERMAL COMMINUTION

With the energy inefficiency of mechanical comminution in mind, many other processes have been studied using thermal shock. There are two different approaches in thermally enhanced comminution, i.e. cryogenic treatment and high temperature treatment.

Cryogenic Comminution

Most materials become more brittle at lower temperature. This phenomenon can cause material problems in the arctic environment, but it can be used beneficially in conjunction with other conventional comminution mechanisms, as in cryogenic comminution of rubber, latex, resin, foods and coal samples. For applications of cryogenic comminution to the mineral industry, Pulverizing Machinery, Division of Mikropul Corp. at Summit, N.J. conducted laboratory test work through Air Products and Chemical, Inc. in Allentown, Pennsylvania (Private communication, 1984).

High Temperature Thermal Comminution

For the high temperature treatment, direct heating of solids can sometimes cause comminution. Turba and Rumpf (1964) indicated that barite ($BaSO_4$) samples shattered upon heating to a temperature higher than 530 °C. It is assumed that the shattering was caused by the rapid expansion of water vapor that was included as adsorbed water on the cleavage faces of larger crystals. Kanellopoulos and Ball (1975) studied the fracture enhanced by the thermal weakening of quartzite.

However, most of high temperature thermal comminution utilizes thermal shock. In eletrothermal comminution, the thermal shocks are generated by some electrical means to cause the breakage of the solids. Breakage of rocks using electric energy has been studied using various electrothermal fracturing mechanisms such as electromagnetic induction heating (Matthaei, 1968 and Sarapuu, 1973) , dielectric heating (Sarapuu, 1973), microwave heating (Steudel, 1965 and Matthaei, 1968), plasma heating (Reed, 1962) and electric arc heating (Burlutskii, Vedyaev and Petrenko, 1959); electromagnetic fracturing (Sarapuu, 1973); electron gun comminution (Schumacher, 1969 and 1972); laser comminution (Cahn and Fuerstenau, 1967) and electrohydraulic comminution (Sarapuu, 1973,

Carley-Macauly, et al, 1966 and Bergstrom, 1961). In addition to these abovementioned methods, we have the potential application of electromagnetic propulsion that is the subject of intensive research at present the time. Electromagnetic propulsion of pellets or water can be used to break rocks. Alternatively, comminution by electromagnetic propulsion can be achieved when high speed solid particles traveling in opposite directions are made to collide. Electrothermal and electrohydraulic comminution have been developed and tested in the field for practical applications. But some exotic means of comminution such as electron gun comminution, laser comminution, electromagnetic fracturing, electromagnetic propulsion comminution and microwave comminution are far from practical application at the present time. However, they are probably useful in some special limited applications or useful to future industries in space.

Electrothermal Comminution

The electrothermal gradient in rocks can be developed using direct-contacting electrodes (Anonymous, 1961). Breakage is accomplished by applying normal electirc power of high frequency at high votage to cause electrothermal expansion. The application of power establishes the conducting path due to the dielectric breakdown of resistance between the two electrodes. The temperature in the zone rises rapidly as the high frequency power or pulse of direct current energy dissipates continuously. Heating of this molten channel can be acomplished by a low frequency power source. As described by Kravchenko, Obrastsov and Ustinov (1960), the electrothermal breaking of rocks can be achieved by different methods, i.e. the high frequency only contact electrode system, both high and low frequency systems and high frequency-condenser discharge system. They claim that electrothermal breaking of quartzite containing iron was 5-25 times cheaper than secondary blasting. Sarapuu (1973) described various modes of electrode contact. In the same paper, the field application of the first commercial Electro-Breaker of Electrofrac Corp. was descibed in detail. The unit uses a 500 kva power source for primary and secondary breaking. The consumption of energy decreased when electrodes were drilled into rocks, confirming the results of Kennedy (1971 & 1972) and Res and Chattapadhyay (1987). Electrothermal rock fragmentation tests were carried out successfully at taconite iron mines in Minnesota, Michigan and Missouri (Sarapuu, 1973,1969 & 1965 and Sarapuu, Calhsun and Clark, 1961). Kravchenko, Obrastsov and Ustinov (1960) described the modified LGPZ-60 secondary ore breaker that was similar in design to the above Electro-Breaker of Electrofrac Corp. The unit was successfully tested for secondary breakage at the YuGOK iron ore open pit mine. Most of the electrothermal rock breaking equipment studied in the U.S. and the U.S.S.R. is designed for the low frequency heating of semiconductive ores. For highly dielectric rocks, the design has to be modified.

Electromagnetic Comminution

Sarapuu (1973) and Matthaei (1968) studied rock breakage by electromagnetic induction heating. Electrothermal comminution by electromagnetic induction heating is only applicable to rocks containing magnetic minerals. The rapidly changing electric field causes magnetic hysteresis as well as eddy currents in the magnetic minerals. The resulting energy losses cause thermal stresses in the rocks. The effect of magnetic hysteresis is dominant in highly resistive rocks, while the eddy current effect is most pronounced in conductive minerals such as magnetite. The magnetostriction and reverse piezoelectric effect can also contribute to the above mechanism.

Laser Comminution

Laser comminution was studied by Cahn and Fuerstenau (1967) using a 15-joule ruby laser at a wave length of 6940 angstroms for the development of a portable comminution devise. On irradiation by the laser, no damage to the surface of various types of clear glass, quartz or calcite was observed. The surface of copper sulphate penta-hydrate was dehydrated, but no breakage occured. Some vaporization and fracture occurred in gypsum. All coloured glasses melted or burned. The study indicated that, for laser comminution to be effective, the reflectance on the surface of solids should be low for the absorption of laser energy, and at the same time the internal absorptance of the material should be neither too high nor too low, because solids melt and burn when absorptance is too high. The above study indicates that laser breakage is not an efficient means of comminution until laser technology improves its energy conversion efficiency. Schumacher (1972) also concluded that lasers are not applicable in underground rock breaking due to the low thermal conduction of rocks and the low overall energy efficiency of the laser system.

Electron Beam Comminution

Schumacher (1972) suggested that electron beam comminution is more effective than laser beam comminution. The power conversion efficiency of an electron gun is very high at about 90 %. The electrons act as bullets, and their energy is carried as kinetic energy, not in the form of electic energy. Electron beam comminution works by combining high temperature melting and thermal shock. The laboratory study indicated that various rocks and minerals were effectively broken using the electron gun. The energy required for comminution was 30, 100 and 500 Joule/cm^3 for copper ore, igneous rocks containing quartz and gabbro, respectively, compared with the comminution energy required for conventional mechanical grinding of soft rocks (100 Joule/cm^3) and hard rocks (1000 Joule/cm^3).

Micro-wave Comminution

Schumacher (1972) also indicated that high frequency micro-waves can also be used as a source of thermal shock in rocks. However, the process was considered to be very energy inefficient.

Electroacoustic Comminution

Electroacoustic comminution is a two-stage electrothermal and ultrasonic comminution that Goldberger, Epstein and Parekh (1982) and Parekh, Epstein and Goldberger (1984) studied for selective comminution of molybdenite and pyrite along the grain boundaries within the matrix of silicate minerals.

IV. ELECTROHYDRAULIC COMMINUTION

PRINCIPLE

Electric sparks can cause great damage to materials, as amply demonstrated by the destructive power of lightening during summer storms. We often experience ceramic insulators breaking into fragments when they fail and electric sparks are generated. However, the destructive power of electric sparks can be tamed and used to benefit us. In electrohydraulic comminution, an electric arc is generated underwater to produce a shock wave in water which contains the solids that are to be broken. High voltage energy from a transformer is rectified and stored in condensors to be released at the proper moment as an underwater electric arc. The electric arc under water generates a shock wave through the liquid medium by the rapid expansion and collapse of the arc zone, so that solid particles in the water break apart, resulting in comminution. Losev, Melikova, Saprykin and Yutkin (1959) claimed that pressures as high as 100,000 atmospheres can be developed in this way. When a channel of electric spark is formed across the water gap between the tips of electrodes, water dissociates into hydrogen and oxygen, and about 10-20 % of the gases become ionized. The channel is then quickly filled with this ionized gas, plasma, and the un-ionized gases, thus generating the primary shock wave by pushing the wall aside. According to Maroudas, Johnston and Yigit (1966) and Carley-Macauly, Hitchon and Maroudas (1966), the front of this primary shock does the major damage to the solids. However, Yutkin (1955) and some of the Russian investigators contend that a secondary cavitation shock wave, which is formed when the plasma collapses after the discharge is discontinued, is the main cause for the breakage of solids, causing tensile stresses inside solids. Maroudas (1967) claimed that the primary shock is the stronger of the two and causes the bulk of the damage, while the weak cavitation shock plays the secondary role.

The primary breakage mechanism of electrohydraulic comminution is "scabbing" or Hopkinson fracture (Rinehart and Davids, 1960 and Kolsky, 1963) and secondary comminution can occur by Rayleigh surface wave (Bowden and Field, 1964), as dicussed in the previous section on shock wave comminution. Carley-Macauly, Hitchon and Maroudas (1966), Carley-Macauly (1968) and Hitchon and Carley-Macauly (1972) studied detailed mechanism for electrohydraulic comminution. Electrohydraulic comminution was influenced by the decay of shock pressure and the spreading of the wave during transmission as well as by the initial pressure and width of the pulse. Yigit, Johnston and Maroudas (1969) indicated that the causes of fracture are primarily tensile effects, and one of the most important factors is the ratio of the size of the specimen to the wave length of the shock pulse.

ENERGY EFFICIENCY OF ELECTROHYDRAULIC COMMINUTION

According to Suits' theory (1935), the conversion of electrical energy into acoustic shock energy is one of the most efficient means of energy conversion. The theoretical electroacoustic efficiency, the ratio of acoustic shock energy to electric energy, is directly proportional to the density of liquid meium, the velocity of the shock front and the temperature of the plasma, and can be as high as 100 %, as proven by Martin (1970) experimentally. However, the electrical energy is converted not only to useful mechanical work in moving the water, but also to wasteful dissociation energy of water for the generation of oxygen and hydrogen gases, to ionization energy for the ionization of 10-20 % of the gases, to thermal energy to heat the arc zone, to radiation energy, and to acoustic energy. Effective comminution occurs only in the vicinity of the spark channel. Although some Russian studies claim that high energy efficiency was obtained, Bergstrom (1961) indicated that the claims can not be confirmed because very little information on the product particle size is available. On the other hand, almost all electrohydraulic comminution studies in the Western world indicate that much more research has to be done to improve the energy efficiency. Frungel and Keller (1957), Roi and Frolov (1958) and Martin (1960) studied the efficiency of electroacoustics with very poor results. The transfer of shock energy from liquid to solid is only about 10 % in electrohydraulic metal forming (Maroudas, 1967). As a result, electrohydraulic comminution has not been a practical proposition due to its disappointingly low energy efficiency. However, Maroudas, Johnston and Yigit (1966) and Maroudas (1967) claimed that the Bond Work Index of 20 kwh/ton was achieved close to the mechnical Work Index of 15 kwh/ton by half-exposing the granite rock specimens to air. They explained that the acoustic impedance of water and solid are of the same order, hence the shock waves are easily transfered between them without much reflection at the interface. On the other hand, the acoustic impedance of air is about 1000 times lower than that of solids or water. Therefore, once the

shock waves are transfered from water to solids most of them will be reflected back into solids at the solid-liquid interface, causing great tensile stress inside the solids. This was accomplished by half-immersing solids in water and half-exposing the solid into air.

The comminution effect depends very much on the sharpness of the shock wave fronts. This sharpness of the wave fronts is affected by many factors such as gap size of both the control circuit and the electrode, the capacities of the condensors, and the resistance and self-inductance of the circuit. The difficulties experienced by many investigators in the field of electrohydraulic comminution include the very short life of condensors, underwater electrodes, and the insulation of the underwater electrodes.

POTENTIAL BENEFITS

1. Considering the low energy efficiency of conventional mechanical comminution (1-5% in terms of new surface area generated), electrohydraulic comminution has high potential to improve energy efficiency, because the solid body is immersed in the liquid medium that transfers powerful shock energy.
2. The level of comminution energy can be controlled easily for the achievement of the desired degree of size reduction. This might also be advantageous in tunneling or anywhere that a high degree of breakage control is required.
3. Electrohydraulic comminution will be more selective due to the breakage along grain boundaries, as in the Snyder Process.
4. Electrohydraulic comminution is highly selective for the comminution of mixtures of different materials, due to the specific energy level. For example, only pyrite is crushed in a mixture of pyrite and flint, and only flint in a mixture of flint and granite.
5. Electrohydraulic comminution produces an unusally cubic fracture with a very low fines content.
6. There are no such comminution media as steel balls and rods to contaminate the ground products. Electrohydraulic comminution is ideal for contamination-free comminution of materials that require high product purity, as in the pharmaceutical industry or optical glass industry.
7. The non-contact comminution mechanism of elctrohydraulic comminution is advantageous for the comminution of radioactive or irradiated materials.
8. An elctrohydraulic drill is less noisy than a mechanical pneumatic drill.
9. An elctrohydraulic drill can be used when non-explosive breakage of rock is required.
10. Electrohydraulic comminution devices have no moving parts, making them simple to operate and maintain, and cost effective.

POTENTIAL PROBLEMS

1. Simultaneous generation of the explosive gases of hydrogen and oxygen.
2. The danger of electric shock.
3. The short life of electric components such as capacitors, electrodes and insulators.
4. The potentially high energy efficiency of electrohydraulic comminution is yet to be proven industrially.

DEVELOPMENT HISTORY

Svedberg (1905) produced metallic colloids using the discharge of a capacitor through a liquid medium, similar to electrohydraulic comminution. Michel-Levy and Maraour (1934) generated a high intensity shock wave using capacitor discharge. Suits (1935) proved that during the initial expansion of the spark channel,the electroacoustic efficiency, i.e. the conversion efficiency of capacitor energy into shock wave energy, could be greater than 97 %. The obvious conclusion is, at least in theory, that high intensity electrical sparks are the most efficient means known of converting electrical energy into acoustic energy. Stanyakovich (1944) pointed out the potential use of liquid media as a transducer of high power impulse. Yutkin (1955) wrote a book on electrohydraulic effects and discussed the breaking of rocks, the forming of metal sheets and the atomizing of liquids. Frungel and Keller (1957) and Roi and Frolov (1958) obtained electrohydraulic efficiencies 1-50 %. Martin (1960) proved Suits' theory (1935) by obtaining an experimental electrohydraulic efficiency close to 100 % at the initial stage of discharge. But, overall electroacoustic efficiency rarely exceeds 50 % due to various energy losses through the dissociation of water, the ionization of gases, the heating of the arc zone, the radiation of lights, and the generation of noise. There is additional energy loss at the interface between solids and liquid. Consequently, the energy efficiency of electrohydraulic comminution have been disappointingly low, in comparision with conventional mechanical comminution. Therefore electrohydraulic comminution remains largely exploratory at the present time.

Dzimianski and Person (1952), Bergstrom (1958) and Kaeser (1959) all at Allis-Chalmers Manufacturing Corp. studied electrohydraulic communition and arrived at the conclusion that the process is even less efficient than conventional mechanical comminution, according to Bergstrom (1961). Early and Martin (1957) and Strong (1957) used hydraulic shock developed by underwater electric discharge to punch holes in sheet metal. Electohydraulic metal forming was studied by many investigators such as Freiday (1959), Peckner (1960) and Gilchrist (1966). Gardener (1964) studied the cleaning of castings using electrohydraulic sparks.

However, much of the practical development of electrohydraulic comminution has taken place in the U.S.S.R. as indicated by Kravchenko (1957),Stolyarov (1958), Epshteyn (1960), Kravchenko, Obrastsov and Ustinov (1960) and Bergstrom (1961). Yutkin (1955 & 1958) pioneered electrohydraulic studies and the experimental results of crushing and grinding were reported by Kravchenko (1957). The application of electrohydraulic fracturing in the Soviet coal industry was reported by Protodyakonov (1958) and anonymous (1959). Losev, Melikova, Saprykin and Yutkin (1959) reported that electrohydraulic comminution devices similar to the one developed by Yutkin (1959) can produce pressures as high as 100,000 atmosphere to micronize brown coal to 10 um. Bergstrom (1961) quoted Russian literature that an electrohydraulic crusher was used for the comminution of contamination-free optical glass at 100 lbs/hour and for the comminution of chalk at 500 lbs/min. No product size was given, however, to make an estimation of the energy efficiency impossible.

The initial development studies on electrothermal fracture of rocks was carried out by General Electric Co. in cooperation with the Montana School of Mines under a reasearch grant from Anaconda Co. (Anonymous, 1961 and Young, 1963). Sarapuu (1962, 1965a, 1965b, 1969a, 1969b & 1973) and Sarapuu, Cahlsun and Clark (1961) studied various means of electrothermal and electrohydraulic comminution. Whitham (1965) developed electrohydraulic comminution equipment, as disclosed in a U.S. patent. Sarapuu (1973) reported that the Electro-Breaker of Electrofrac Corp. was tested in the field successfuly for primary and secondary breakage of taconite iron ores. The first commercial unit used 3,000 volts and 1,500 amperes to produce 500 kva nominal power. It took 2-3 minutes to break 5-10 ton boulders using 1-2 kwh/ton of power at 200-250 kva. The design and specification of the Electro-Breaker is similar to the one developed in the Soviet Union.

The Atomic Energy Research Establishment in Britain studied the mechanism of electrohydraulic comminution in some detail for possible application of the process to the non-contact comminution of radioactive or irradiated solids. Carley-Macauly, Hitchon and Maroudas (1966) used a special electric circuit with low inductance (0.1-0.2 uH) for fast discharges. Gravel, alumina and graphite were comminuted from 1 cm down to 200-300 um, using a voltage of 20-85 kv, a spark gap length of 0.5-4.0 cm, and a capacitance of 0.002-0.125 uF. The maximum yields obtained were 20-30 and 3-4 kg/kwh for gravel and alumina, respectively. The results indicated that it was more efficient to use small capacitances at high voltages for the tougher alumina, while softer sparks were more efficient for the less tough gravel. The Bond Working Index for elctrohydraulic comminution was 100, 400 and 300 for gravel, aluminaand graphite, respectively. It was apparent that electrohydraulic comminutionis some 10 times less efficient in using the energy stored in the capacitors

than the conventional mechanical comminution method. In addition, the maximum efficiency of the charging circuit is about 50 %. The authors concluded that the inefficiency of the process was caused by the rapid attenuation of the shock pulse as it moved outward even at the low capacitances used, so that the energy quickly degenerated into a wide pulse of relatively low peak pressure. This problem might be eliminated if one borrowed the technology of the interior structural design of nuclear bombs to concentrate the explosive shock waves at the center of the comminution chamber. Another study by Carley-Macauly (1968) emphasized the importance of the rapid recirculation of the solid particles to the comminution zone at the spark gap. Hitchon and Carley-Macauly (1972) studied glass spheres, ceramic spheres and quartz particles. Experiments with an array of glass or ceramic spheres indicted that the yield per spark increased during the first few sparks due to gradual completion of the fractures. However, the yield per spark was decreased with quartz after the first spark, indicating that preexisting cracks were extended during the electrohydraulic comminution. Andres (1977) studied the effect of two liquid media, water and transformer oil, for electrohydraulic selective comminution of apatite-nepheline ore. Maroudas (1964 & 1966), Maroudas and Yigit (1966) and Maroudas, Johnston and Yigit (1966) claimed that the efficiency of electrohydraulic comminution can be improved very much by half-exposing the solid to air. They claim that the shock wave can be trapped inside solids due to the great differences in the acoustic impedances between solids and air.

SELECTIVITY IN ELECTROHYDRAULIC COMMINUTION

Yigit, Johnston and Maroudas (1969) found that electrohydraulic comminution is highly selective for the comminution of mixtures of different materials due to the specific energy level it employs. For example, only pyrite is crushed from the mixture of pyrite with flint, and only flint from the mixture of flint with granite. Parekh, Epstein and Goldberger (1977) and Goldberger, Epstein and Parekh (1982) indicated that electrohydraulic comminution broke the porpyritic molybdenum ore selectively along the grain boundaries of molybdenum and pyrite within the matrix of silicate minerals. Andres (1977) found in his study of apatite-nephelin ore that the selectivity in electrohydraulic comminution was much higher than that in conventional mechanical comminution.

PARTICLE SHAPE OF PRODUCT

Yigit, Johnston and Maroudas (1967) found that electrohydraulic comminution produces an unusally cubical shape of fracture with very low fines content. Hitchon and Carley-Macauly (1972) also observed that the electrohydraulic comminution of glass spheres produced very few needle-shaped particles. Maroudas (1967) also mentioned that electrohydrauluc comminution can give a precision and symmetry of fracture which is unique.

LOW CONTAMINATION IN ELECTROHYDRAULIC COMMINUTION

Carley-Macauly, Hitchon and Maroudas (1966) emphasized that electrohydraulic comminution producess much less product contamination, comparing the consumption of grinding media.

ELECTROHYDRAULIC DRILL

The proper application of electrical energy to drilling bits, similar to cathodic protection of corrosion, through an arrangement of electrods can reduce the wearing rate of drilling bits, according to Hoenig, Zanoni and Griffith (1983). Carstens (1970) discussed a heat-assisted tunnelboring machine that used electrothermal energy to weaken the rock face. Armstrong(1965) studied the drillng of rocks using electrothermal melting.

The principle of electrohydraulic comminution can also be applied for the drilling or boring of holes in rocks. In electrohydraulic drilling, underwater electrical sparks are generated between a rotating central electrode and successive teeth on the edge of the outer bit (Bergstrom, 1961, Maroudas, 1967 and Sarapuu, 1973). Rock is broken with each successive electric discharge. The broken piece of rocks are flushed out through the annular space between the walls of the drilled hole and the bit. The Russian design used 25 kv of electric power and 0.2 mfd of electrical capacity to deliver two 0.7 cm long sparks of 312 watt-seconds. The electrohydraulic drill bored a 4 cm diameter hole on a clayey-quartzitic-slate at a speed of 5 cm/min under the thrust of 1.5 kg. In some other cases, drilling speeds of 0.8, 3.0 and 20 inches/min were obtained for granite, iron ore and concrete, respectively, using the same electrohydraulic drill.

Sarapuu (1962 & 1973) described the successful field application of electrical disintegration drilling adapted from a mechanical drill. This is not an electrohydraulic drill in the strict sense that the electrical power is applied between the drilling bit and the electric ground at nearby surface. He reported that the penetration rate of a rotary drill with 20,000 psi down pressure and 6¼ inch roller bit had improved from 8 inches per hour without electric power to 36 inches per hour with 60 kva of electric power. Sarapuu (1973) also described an electrohydraulic drill with two electrodes at the tip of a drill bit. Szuck, Riddell and Singh (1982) reported that commercial electric-hydraulic drills improved the rate of drilling at various Ni-Cu mines of Falconbridge Nickel Mines Ltd. The average drilling rate increased to 0.82 m/min with an electrohydraulic jumbo from 0.21 m/min with a conventional pneumatic jumbo. They found that electrohydraulic drilling is more energy efficient, quieter and easier to handle. It requires less maintenance and one small portable compressor can replace the large surface compressors.

V. CONCLUDING REMARKS

Various means of comminution and their mechanisms are briefly reviewed with an emphasis on electrohydraulic comminution. At the present time, almost all comminution is being done using conventional mechanical comminution devices such as crushers, grinding mills and disk pulverizers. Other non-mechanical comminution that has been studied include shock wave comminution (the Snyder process, hydraulic comminution and mining, ultrasonic comminution, and elelctrohydraulic comminution) and thermal comminution (low temperature cryogenic, high temperature thermal, electrothermal, electromagnetic, laser, electron beam, micro-wave and electroacoustic comminution).

Conventional mechanical comminution is very inefficient in terms of energy used to produce new surface area, because only a fraction of time and working surface are utilized for actual comminution at any given moment, and because the efficiency is very poor when energy is transfered from electrical to comminution energy via mechanical means that utilize high compressive stress rather than low shear or tensile stress.

Among many mechanical comminution devices, it is recognized that a disk pulverizer deserves further concerted R&D effort. Although it has some shortcomings such as high rate of disk wear and low throughput, they are not insurmountable with the advent of modern technology. A disk pulverizer is inherently superior to other mechanical comminution devices, because its plane-contact grinding mechanism stands out from those of other comminution devices that use line or point contact. The contact period of the working surface is 100 % of the operating time. It utilizes low shear stress rather than high compressive stress to break solid particles. As in a flywheel, large rotating disks can save energy as angular momentum. All solids must go through a pulverizer without by-passing. Mechanical transfer of electrical energy to comminution energy has been the most familiar field to comminution engieers. For some applications, disk pulverizers produce more flaky products. Short-term intensive R&D on the process promises to yield very high potential rewards.

All other non-contact and non-mechanical means of comminution (e.g. laser, particle beams and plasma comminution) are at early stages of studies in laboratories and are far from being practical enough for application to the minneral processing industry at the present time.

Electrohydraulic comminution occurs when a shock wave is generated using an electric spark in water containing solid particles. Among various means of non-conventional comminution, electrohydraulic comminution is the only one that has been developed far enough for a field trial. Although a large scale industrial application of the process is yet to be realized, it has long term potential to achieve high efficiency of comminution energy. The process even at the present time, may find limited use for some specific applications, e.g. non-contact comminution of radioactive materials, contamination-free comminution of optical glass, or non-explosive and non-mechanical breakage of rocks. The process can achieve high energy efficiency due to its unique mechanism of comminution. Some of the studies indicate that the comminution can be made selective by controlling energy input. Selective breakage along the grain boundaries were also observed. It produces unusually cubic fracture with a very low fines content.

There are three main applications of electrohyraulic comminution, i.e. primary and secondary rock breaking in mines, electrohydraulic drilling of rocks and electrohydraulic comminution of fine particles. Some equipment was designed and tried for those applications mainly by the researchers in the Soviet Union and by those in the United States who had connections to the Russian experience. The high energy efficiency that was claimed by some investigators is yet to be proven conclusively. Underwater electric spark posesses the danger of electric shock. Underwater electric sparks produce hydrogen and oxygen gases that can cause explosion. The short life of various electric components such as capacitors, electrodes and insulators has to be improved.

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